

# Vortex Fluid State below an Onset Temperature $T_0$ of Solid $^4\text{He}$

Andrey Penzev, Yoshinori Yasuta, and Minoru Kubota\*

*Institute for solid State Physics, University of Tokyo, Kashiwanoha 5-1-5, Kashiwa, 277-8581, Japan*

(Dated: February 4, 2008)

Detailed studies of the AC velocity  $V_{ac}$  and  $T$  dependence of torsional oscillator responses of solid  $^4\text{He}$  are reported. A characteristic onset temperature  $T_0 \sim 0.5$  K is found, below which a significant  $V_{ac}$  dependent change occurs in the energy dissipation for the sample at 32 bar. A  $V_{ac}$  dependence of the "non-classical rotational inertia" fraction (NCRIF) also appears below  $\sim T_0$ . This value of  $T_0$  excludes the possible explanation of supersolid by liquid superfluidity in grain boundaries or other liquid related origins. The  $\log(V_{ac})$  linear dependence was found in NCRIF. Furthermore, this linear slope changes in proportion to  $1/T^2$  for  $40 < V_{ac} < 400$   $\mu\text{m/s}$ , then crosses over to  $\sim 1/T$  for larger  $V_{ac}$ . We discuss properties of the vortex fluid proposed by Anderson above  $T_c$  and below  $T_0$ .

PACS numbers: 67.80.bd, 67.25.dk, 67.25.dt, 67.85.De.

Since the first report of "non-classical rotational inertia" (NCRI) in solid  $^4\text{He}$  samples by Kim and Chan[1], confirmation has come from several torsional oscillator (TO) experiments[1, 2, 3, 4, 5], including by the present authors. This finding has been discussed in connection to the NCRI of a supersolid as originally proposed by Leggett[6]. A review paper by Prokof'ev[7] is valuable for understanding recent work up to December 2006. An important conclusion is that the observed phenomena seem to be more complicated than the original proposal of a BEC of vacancies or other imperfections. Much excitement has been generated by the recent observation of a remarkably large NCRI fraction, NCRIF, under appropriate experimental conditions. Rittner and Reppy[4] found the NCRIF increased in quench-cooled samples as the distance between closely-spaced, concentric walls confining the helium was made smaller. These authors attribute the increase of NCRIF to increased disorder in the sample. NCRIF greater than 20% of the total mass could be achieved[4], indicating simple mechanisms involving only a small fraction of the solid helium are not adequate as explanations of the observed new phase.

According to a recent theoretical proposal by P.W. Anderson[8], the results previously attributed to NCRI might be caused by non-linear-rotational-susceptibility, NLRS, on account of features shared with non-linear-magnetization seen in some underdoped (UD) cuprate HTSC[9] below an onset temperature  $T_0$  but above  $T_c$ , where the resistivity is non-zero. He discusses the linear dependence of NLRS on  $\log(V_{ac})$  as evidence for a vortex fluid (VF)[8]. A fundamental background for the VF state is as follows. The reported occurrence of NCRI above or near 100 mK is way too high  $T$  for the appearance of BEC of any of the known excitations in solid He from the known concentrations, whereas VF state can appear with the help of vortex excitations in lower dimensional (D) subsystems in the solid He, where quantized vortices have much lower energies and are possibly thermally excited as in 2D Kosterlitz-Thouless(KT) systems. VF state is without 3D macroscopic coherence, and does

not support superflow. More recently Kojima's group reports[10] a significant change occurring below 40 mK in the TO response time when excitation  $V_{ac}$  is changed. They also report hysteresis below about this temperature, possibly an indication of a real  $T_c$ . Reppy[11] claims his group observes similar hysteresis below a corresponding  $T$  although their "NCRIF" is orders of magnitude larger. Clark et al.[12] find NCRIF appearing at much lower  $T$  in either ultra pure  $^4\text{He}$  or in  $^4\text{He}$  single crystals in comparison to that seen in samples prepared by the usual blocked capillary method using the usual commercial grade of  $^4\text{He}$ , which typically contains about 0.3 ppm  $^3\text{He}$  impurity. Their saturation NCRIF has been from 0.03% to 0.4%[12].

An interesting and significant observation is that the NCRIF for a  $^3\text{He}$  concentration of 0.3 ppm may differ by more than 3 orders of magnitude among samples prepared under different conditions[4, 10, 12] while the characteristic temperatures for the phenomena change by no more than a factor of 2 to 3. For example, the temperature for the energy dissipation peak  $T_p$ , is below or around 100 mK. The onset temperature,  $T_0$ , below which the NCRI fraction begins to appear has been reported to be 250 mK to 300 mK[1, 2, 3, 4], except for [5, 12, 13]. This implies some low D subsystem exists in solid  $^4\text{He}$  and the characteristic temperatures are determined primarily by the subsystem local density while the number density of the subsystems determines the overall NCRIF. The latter may be increased by externally induced disorder[4]. All these observations seem to imply the conditions for the VF state are satisfied and  $T_0$  would imply the appearance of the low D "condensate", as also discussed for UD cuprates[9].

We investigated  $T_0$  also on account of a claim the observed phenomena might not be an intrinsic property of the solid[13] but instead could be caused by superfluid liquid at the grain boundaries. However, experimentally  $T_0$  has not been established and it is not known what changes at  $T_0$  because NCRI appears very gradually. This paper describes experiments on rather stable

$^4\text{He}$  samples for which NCRIF extrapolated to  $T = 0$  K is quite small, that is  $\text{NCRIF}(0) < 0.05\%$ . We report our observations and discuss the determination of  $T_0$  and appearance of the VF phase below  $T_0$  and above some  $T_c$ .

The samples studied were at pressures between 32 and 35.5 bar and all showed similar behavior except for the absolute value of the dissipation. All samples remained quite stable as long as we kept them colder than about 700 mK; with this stability we hoped to study the most fundamental properties of solid  $^4\text{He}$ . Most of the presented data are for a sample which remained reproducible throughout 45 days of experiments, but quite representative of all. The measurements were performed on the ISSP fast rotating cryostat[14]. This provided much more reliable and reproducible data compared to our previous supersolid experiments[5] because this cryostat is far more rigid while also having much more mass, about 10 metric tons, with superior vibration isolation. In addition, the ability to rotate the samples is now available and we plan presentation of results for DC rotation in future publications. The BeCu TO has a 15 mm long torsion rod with 2.2 mm outside diameter and a 0.8 mm coaxial hole serving as the filling line. The cylindrical sample cell made of brass is mounted on a BeCu base integral with the torsion rod, with threaded fitting and sealed with Wood's alloy. The interior sample space is 4 mm high and has 10 mm diameter. Below 4.2 K the resonant frequency of the TO is approximately 1002 Hz with  $Q \approx 1.7 \cdot 10^6$  as determined from the free decay time constant. The samples were prepared by the blocked capillary method from  $^4\text{He}$  gas of commercial purity ( $\approx 0.3$  ppm  $^3\text{He}$ ) with cooling along the melting curve at the rate  $\approx 2 - 5$  mK/min. No special annealing was attempted but the samples were cooled slowly, over a period of a few hours, from the melting curve to 1 K. The final pressure of solid was estimated from a sharp drop in TO amplitude at the melting temperature measured during slow ( $\approx 0.55$  mK/min) heating after completion of the measurements[5]. The change of period caused by the solidification of the sample is  $\Delta p_{\text{load}} \approx 2.4 \mu\text{s}$ .

In order to discuss solid  $^4\text{He}$  internal friction separately from empty BeCu TO properties we have chosen the quantities associated with solid  $^4\text{He}$  as below, to facilitate comparison with results from other types of experiments on solid  $^4\text{He}$ . Energy dissipation(internal friction) in the solid  $^4\text{He}$  sample  $\delta$  is evaluated from TO measurements taking similar considerations of the composite TO[15] where the  $^4\text{He}$  sample itself is regarded as a part of the composite oscillator and also compared with sound measurements[16]. Using additivity of dissipated energy  $\Delta\varepsilon$  and the stored energy  $\varepsilon$  for the composite TO per cycle of oscillation, the definition of internal friction  $Q^{-1} = \Delta\varepsilon/2\pi\varepsilon$  gives

$$\begin{aligned}\Delta\varepsilon_{\text{total}} &= \Delta\varepsilon_{\text{empty}} + \Delta\varepsilon_{\text{solid}}, \\ \varepsilon_{\text{total}} &= \varepsilon_{\text{empty}} + \varepsilon_{\text{solid}},\end{aligned}$$

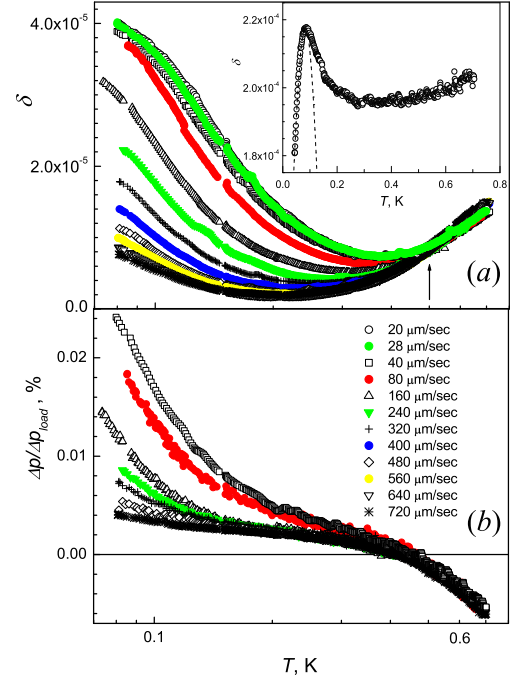


FIG. 1:  $T$  dependence of energy dissipation  $\delta$ (a) and  $\text{NCRIF} = \Delta p / \Delta p_{\text{load}}$ (b) at various  $V_{ac}$ . The values of  $\delta$  are presented without any artificial shift. An arrow indicates  $T_0$ , across which  $V_{ac}$  dependence changes the sign. Some data are omitted for clarity (all the data on  $V_{ac}$  dependence are plotted in Fig. 2). The inset in (a) indicates a typical energy dissipation peak with somewhat higher  $T_p$ . The low  $T$  part of the peak was fitted with a Gaussian: dashed line. See Fig.2 caption for the determination of zero for NCRIF in (b).

$$\frac{\Delta\varepsilon_{\text{total}}}{\varepsilon_{\text{total}}} = \frac{\Delta\varepsilon_{\text{empty}}}{\varepsilon_{\text{empty}} + \varepsilon_{\text{solid}}} + \frac{\Delta\varepsilon_{\text{solid}}}{\varepsilon_{\text{empty}} + \varepsilon_{\text{solid}}}. \quad (1)$$

In our case  $\varepsilon_{\text{empty}} \gg \varepsilon_{\text{solid}}$ , because the stored energy  $\sim I$  and  $I_{\text{empty}} \gg I_{\text{solid}}$ . Therefore  $\delta$  is given as

$$\delta = \frac{\varepsilon_{\text{empty}}}{\varepsilon_{\text{solid}}} (Q_{\text{total}}^{-1} - Q_{\text{empty}}^{-1}); \quad (2)$$

with

$$\frac{\varepsilon_{\text{empty}}}{\varepsilon_{\text{solid}}} \approx \frac{I_{\text{empty}}}{I_{\text{solid}}} \approx \frac{p_{\text{empty}}}{2\Delta p_{\text{load}}} \approx 210 \text{ (for our cell)}, \quad (3)$$

where  $I_{\text{empty}}$  and  $I_{\text{solid}}$  are the moment of inertia of empty BeCu TO and solid sample respectively.

The upper graph Fig. 1(a) shows  $\delta$  in the solid  $^4\text{He}$  sample while the lower graph(b) gives the relative shift of the period,  $\Delta p / \Delta p_{\text{load}}$  corresponding to the NCRIF of the solid  $^4\text{He}$  as a function of  $T$  for various AC cell rim velocities  $V_{ac}$ . The inset in Fig. 1 shows an example of peaks appearing in the data at  $T_p$  for samples for approximately the same pressure. The peak is asymmetric as compared with a Gaussian curve fitted to the data on the low  $T$  side. All the data in the main graphs are for  $T > T_p$  for the sample at 32 bar.

It is important to notice both the period and dissipation  $\delta$  are changing over the entire  $T$  range for the measurements. Above 0.5K  $\delta$  increases and the relative period decreases as  $T$  increases. In addition, a much stronger apparent dependence on  $V_{ac}$  begins for  $T$  below 0.5 K, especially for the energy dissipation. The change of the sign of the  $V_{ac}$  dependence allows the assignment of a unique characteristic temperature  $T_0 = 0.5$  K as indicated by an arrow. At  $T > 0.5$  K (normal region) the absolute value of  $\delta$  can be compared with available data obtained by other techniques (sound, elastic deformation). The  $\delta < 2 \cdot 10^{-5}$  we find is very much smaller than other available data[17] and the resonant dislocation vibration mechanism analysis[18]. Based on the present size of  $\delta$  the most probable mechanism for dissipation is thermoelectric internal friction, and not dislocation motion[17] as has been proposed for larger excitation experiments. The original data in Fig. 1(b) form a set of parallel curves above  $\sim 0.45$  K, but for the graph they have been shifted to coincide in this  $T$  range.

A striking difference between the properties seen in Fig. 1(a) in comparison with other superfluid systems is that the dissipation peak is largest for the smallest excitation velocity. This behavior is opposite to what is seen for a KT transition[19], or the superfluid transition in 3D He film system[20], or for bulk liquid  $^4\text{He}$  in Vycor[21], all systems in which the dissipation increases when the excitation exceeds some critical value including 0.

In the following we consider this unusual behavior as coming from fluctuations in the VF state, which is regarded as a kind of superfluid turbulent state. Fluctuations are controlled by external rotation[22] and characterized by a distribution over a certain momentum space[23]. The width of this distribution is primarily determined by both the longest straight vortex line length, which is of the order of system size, and the smallest length scale of the vortex tangle or that of vortex rings. In other words, what has been claimed to be a critical velocity is actually a characteristic velocity of the turbulence. Further analysis made this point clearer.

The NCRIF and  $\delta$  as a function of  $V_{ac}$  are analyzed at different  $T$ 's below 300 mK in Fig. 2. All the data are taken from the same data set directly from Fig. 1. If we plot data at higher  $T$ 's, then we obtain almost horizontal displays of data for each  $T$ , in the same frame as in (a) for  $\delta$ , and the same is true for NCRIF, but we need to lower the frame bottom to include higher  $T$  data. In Fig. 2 NCRIF is constant at low  $V_{ac}$  and starts to decrease above  $\approx 10$   $\mu\text{m/s}$ .

The most important feature, however, is the linear dependence on  $\log(V_{ac})$ . This dependence was observed previously in an annular cell [1] and supports the VF model[8]. In Fig. 2(b) we observe two velocity regions where linear dependence on  $\log(V_{ac})$  is seen; one from 40 - 400  $\mu\text{m/sec}$  and the other above 500  $\mu\text{m/s}$ . We can also estimate the characteristic  $V_{ac}$  corresponding to

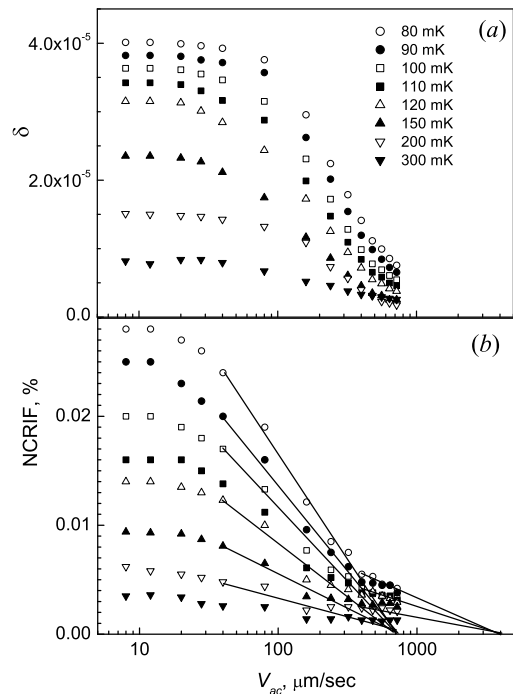


FIG. 2:  $\delta$ (a) and NCRIF(b) as a function of  $V_{ac}$  at  $T < 300$  mK. The solid lines in (b) show the nearly linear dependence on  $\log(V_{ac})$  for two  $V_{ac}$  ranges;  $40 < V_{ac} < 400 \mu\text{m/s}$  and  $V_{ac} > 500 \mu\text{m/s}$ . The slope for each range has a unique  $T$  dependence given in Fig. 4. Extrapolated lines are found to converge at a point for each  $V_{ac}$  range. This point of convergence also determines the position of the zero in Fig. 1(b).

suppression of the major part of NCRIF as  $\sim 750 \mu\text{m/s}$ . The characteristic velocity for complete suppression of NCRIF is estimated to be  $\sim 4$  mm/s. Moreover, these characteristic velocities are  $T$  independent within our experimental accuracy. This feature looks similar to  $H_{c2}$  of UD cuprate [9].

Another important observation of Fig. 2 is the similarity between (a) and (b). In order to study the energy dissipation per superfluid mass, or NCRIF, the ratio  $\delta/\text{NCRIF}$  as a function of  $V_{ac}$  for  $T < 300$  mK is shown in Fig. 3. Despite the uncertainty of zero for this ratio, we can see constant level of dissipation at low  $V_{ac}$  and then clear increase of energy dissipation to some peak value. The characteristic  $V_{ac}$  for the peak position is  $\approx 170 \mu\text{m/s}$  for high  $T$  and it has a weak temperature dependence;  $\sim 300 \mu\text{m/s}$  at 80 mK and changes gradually. We suspect that this distribution of energy dissipation for all  $T < 300$  mK may correspond to the characteristics of the VF state. While examining the above evidence we noticed all slopes in the region  $40 \mu\text{m/s} < V_{ac} < 400 \mu\text{m/s}$  showed a simple  $T^{-2}$  dependence in Fig. 2(b), followed by a crossover to  $\sim 1/T$  dependence as plotted in Fig. 4. We do not know the origin of these dependences, but it is interesting to note that it does not include a finite temperature shift like Curie-Weiss behavior as for mag-

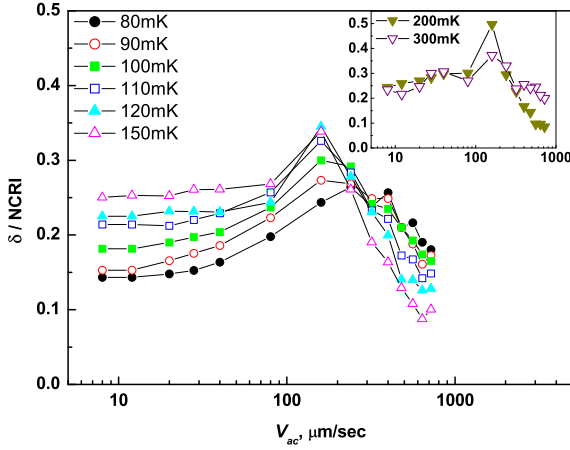


FIG. 3: Dissipation/NCRIF ratio as a function of  $V_{ac}$ . Apart from zero determination difficulty, we observe a gradual increase at low  $V_{ac}$  and a wide distribution over more than a decade of  $V_{ac}$  with a peak. The peak temperature changes from  $\sim 300 \mu\text{m/s}$  at 80 mK to  $\approx 170 \mu\text{m/s}$  for  $T > 110$  mK.

netic susceptibility, but just Curie law like behavior with zero Weiss temperature. Curie Law behavior is observed for metallic spin glasses down to the susceptibility peak. This behavior may also support the idea that we are observing a VF which freezes at some  $T_c$ . In addition we may have found the involvement excitations of different D origins.

While preparing this paper we discovered an interesting study of the mechanical properties in solid  $^4\text{He}$  under shear motion by Beamish's group[24]. We have no concrete idea how solid should behave simultaneously as superfluid and it will become an interesting question.

In summary, we studied properties of NCRIF using TO response from solid helium samples at 32 bar in wide ranges of  $T$  and  $V_{ac}$ . For comparison with other experimental data, the energy dissipation  $\delta$  from solid  $^4\text{He}$  itself was evaluated. We found  $T_0 \sim 0.5$  K from the

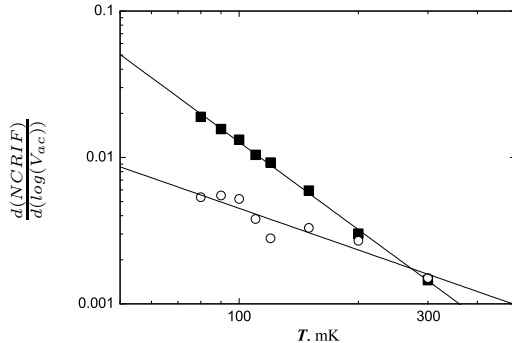


FIG. 4:  $T$  dependence of the slope  $d(\text{NCRIF})/d(\log(V_{ac}))$ . Clear  $1/T^2$  dependence (■) is seen for  $40 \mu\text{m/s} < V_{ac} < 400 \mu\text{m/s}$  and a crossover to  $\sim 1/T$  for larger  $V_{ac}$ (○). It may correspond to dimensional crossover depending on the length scales of the subsystems.

change of  $V_{ac}$  dependence of  $\delta$ . This indicates the appearance of quantized vortices below  $T_0$  and the origin of supersolid is not liquid  $^4\text{He}$  inside solid. The suppression of the NCRIF varies nearly linearly with  $\log(V_{ac})$  until a crossover to another linear dependence with  $\log(V_{ac})$  above  $V_{ac} > 500 \mu\text{m/s}$ . The  $T$  dependence changes from  $1/T^2$  to  $\sim 1/T$ . It looks in support of Anderson's VF picture.

Authors acknowledge T. Igarashi, N. Shimizu and R.M. Mueller's assistance. M.K. is thankful for valuable discussions with P.W. Anderson, D. Huse, and many other colleagues in series of workshops organized by Moses Chan and D. Ceperley, by K. Shirahama, as well as by N. Prokof'ev and D. Stamp. Discussions with M. Kobayashi, M. Tsubota and S. Nemirovskii are heartily appreciated. A.P. thanks JSPS and ISSP for the support.

\* Electronic address: kubota@issp.u-tokyo.ac.jp

- [1] E. Kim and M. H. W. Chan, Nature **427**, 225 (2004), Science **305**, 1941 (2004); Phys. Rev. Lett. **97**, 115302 (2006).
- [2] M. Kondo, S. Takada, Y. Shibayama, and K. Shirahama, J Low Temp Phys **148**, 695 (2007).
- [3] A. S. C. Rittner and J. D. Reppy, Phys. Rev. Lett. **97**, 165301 (2006).
- [4] A. S. C. Rittner and J. D. Reppy, Phys. Rev. Lett. **98**, 175302 (2007).
- [5] A. Penzev, Y. Yasuta, and M. Kubota, J. Low Temp Phys **148**, 677 (2007).
- [6] A. J. Leggett, Phys. Rev. Lett. **25**, 1543 (1970).
- [7] N. Prokof'ev, Advances in Physics **56**, 381 (2007).
- [8] P. W. Anderson, Nature Physics **3**, 160 (2007).
- [9] Y. Wang et al., Phys. Rev. B **73**, 024510 (2006).
- [10] Y. Aoki, J. Graves, and H. Kojima, Phys. Rev. Lett. **99**, 015301 (2007).
- [11] J. D. Reppy, private communication.
- [12] A. C. Clark, J. T. West, and M. H. W. Chan, Phys. Rev. Lett. **99** (2007).
- [13] S. Sasaki et al., Science **313**, 1098 (2006).
- [14] M. Kubota et al., Physica B **329-333**, 1577 (2003).
- [15] Z. S. Li et al., Rev. Sci. Instrum. **74**, 2477 (2003).
- [16] V. L. Tsymbalenko, Sov. Phys. JETP **47**, 787 (1978).
- [17] M. Paalanen, D. Bishop, and H. Dail, Phys. Rev. Lett. **46**, 664 (1981).
- [18] I. Iwasa, K. Araki, and H. Suzuki, J. Phys. Soc. Japan **46**, 1119 (1979).
- [19] D. Bishop and J. Reppy, Phys. Rev. B **22**, 5171 (1980).
- [20] M. Fukuda et al., Phys. Rev. B **71**, 212502 (2005).
- [21] J. D. Reppy and A. Tylar (1991), 'Excitations in Two-Dimensional and Three Dimensional Quantum Fluids', ed. Wyatt and Lauter, Plenum Press, NY, pp. 291-300.
- [22] C. E. Swanson, C. F. Barenghi, and R. J. Donnelly, Phys. Rev. Lett. **50**, 190 (1983), M. Tsubota, T. Araki, and C. Barenghi, Phys. Rev. Lett. **90**, 205301 (2003).
- [23] M. Kobayashi and M. Tsubota, J. Phys. Soc. Jpn. **74**, 3248 (2005).
- [24] J. Day and J. Beamish, arXiv:cond-mat/0709.4666.